



ontario hydro research division

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FAILURE OF 500-kV, 360-MVA AUTOTRANSFORMER (T7) AT HANMER TS ANALYSIS OF SWITCHING TRANSIENTS

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Voltage transients resulting at transformer terminals from routine on and off switching operations were recorded following completion of repairs on the transformer. Switching was performed using transformer breakers at both voltage levels. Maximum phase-to-ground voltages approaching 2 pu were measured while placing the transformer on potential. On all opening operations, the respective breakers interrupted transformer magnetizing current without incurring reignitions. Low-voltage measurements performed on one winding revealed internal resonances in the 8-9 kHz range, which produced voltages-to-ground 8 to 12 times the magnitude of sustained sinusoidal excitation. On the basis of this evidence and knowledge of the circumstances surrounding the failure, it is concluded that the failure was likely initiated by winding resonance excited by multiple reignitions on the switched breaker. Multiple reignitions are considered likely when switching the transformer along with the tertiary reactor using gas-blast breakers (air-blast or SF₆) not equipped with suitable opening resistors. This switching practice should therefore be prohibited.

1. INTRODUCTION

On September 13, 1985 a winding-to-ground fault occurred on the 360-MVA, 500/230-kV T7 autotransformer while being switched out with the 60-MVA reactor connected to its tertiary (Figure 1). Both 230-kV breakers were open, and the transformer was being switched out using 500-kV air-blast breaker PL503. Extensive damage also resulted to two 230-kV surge arresters and all three 500-kV transformer bushings. Transmission Operations Division asked us to investigate this failure and to report on our findings.

Our preliminary investigation raised some concerns regarding the capability of the transformer breakers to switch the tertiary reactor along with the transformer/1/. As a consequence, operating procedures for the station were revised to prohibit such practice/2/.

Low voltage measurements were subsequently performed on T7 in October 1985. Tests were conducted using damped and undamped sinusoidal excitation to search for possible resonance effects, and to measure the resulting voltages internally on the winding. Surge transfer measurements were also conducted at this time. When repairs had been completed in February 1986, instrumentation was installed on T7 to record the switching of the bank into service for the first few operations.

job	file	date	report no.
18-143-202-33	813.6	February 13, 1987	86-317-K

This report presents our findings based on results of the low voltage tests and the monitoring of transients during transformer switching.

2. LOW VOLTAGE MEASUREMENTS

Frequency domain and time domain measurements were performed on B ϕ winding, which had not been involved in the failure, before any repair work had commenced on the transformer. Transformer oil had already been drained from the tank to permit visual inspection of internal damage. Therefore all low voltage measurements were necessarily performed without the oil. Voltage transfer measurements were made at two of the internal tapping points on the winding, identified on transformer nameplate drawing as terminals 18 and 21, both located in the series section of the winding (Figure 2). Terminal 21 was selected specifically because earlier inspection of winding damage had revealed that a flashover had occurred from the vicinity of this terminal to the transformer neutral ground connection lead. Details concerning results of the low-voltage measurements are given in Appendix A. The following findings are of particular interest.

When an 8-9 kHz sinusoidal excitation is applied to the 500-kV terminal with the 230-kV terminal left open, the voltage-to-ground at the monitored locations reaches eight to twelve times the magnitude of the applied excitation. This corresponds to a calculated amplification factor in excess of 16 when account is taken of the turns ratio existing between the excitation and response terminals. The frequency at which such amplification is observed is termed a series resonance frequency of the winding, in reference to resonance phenomenon in series LC circuits where similar amplification is known to occur. When a low impedance termination is substituted in place of the open-circuit on the 230-kV terminal (100 ohms or less in low voltage tests), the above series resonance frequency is replaced by one in the 18-20 kHz range. Connection of the reactor to the tertiary has no effect on any of these resonances.

These results demonstrate that a mechanism exists in this transformer which could produce transient voltages-to-ground internally on the winding, well in excess of those applied at its terminals. What remains to be determined is whether such internal resonance could be excited by switching operations on the respective transformer breakers.

3. MONITORING TRANSFORMER SWITCHING TRANSIENTS

Upon completion of repairs to the transformer, instrumentation was installed to record voltage transients at transformer terminals during routine on-off switching operations. The transformer was switched on and off potential from the 230-kV bus as well as from the 500-kV bus. The tertiary reactor was left out of service during all switching operations because of an operating restriction prohibiting switching of the reactor using the high voltage breakers/2/. Transformer T6 also remained off potential for the duration of these switching operations.

Phase-to-ground voltages on the 230-kV and 500-kV transformer terminals were recorded along with three-phase currents on the switched breaker. In order to record the high frequency voltage transients associated with transformer switching, use was made of the existing 230-kV and 500-kV bushing potential devices at the transformer terminals. The secondary circuit on each device was modified to ensure accurate reproduction of high-frequency voltage transients. All quantities were recorded on light sensitive paper using an Electro-Magnetic Oscillograph, and on a multi-channel analog tape recorder. In addition, all phase-to-ground voltages were recorded using a digital oscilloscope (NICOLET Model 4094) at sampling rates of up to 100 kHz per quantity.

T7 can be switched by any one of four breakers as shown in Figure 1: 230-kV oil circuit breakers HL23 & HL25, and 500-kV air-blast breakers PL503 & PL504. Detailed specifications on the breakers are given in Appendix B. Transients resulting from switching T7 using each of these breakers were recorded.

3.1 Switching T7 Transformer using 230-kV Breakers

The two 230-kV oil circuit breakers are identical units. Their performance therefore ought to be similar. With this in mind, two close-open switching operations were performed on HL25 and only one on HL23. No significant transients resulted on opening operations, which indicates that no reignitions occurred on opening. The following discussion is concerned principally with closing transients.

On a closing operation, current is initially established through 504 k Ω per pole resistors on both breakers. This produced a 60-Hz voltage of about 0.25 pu at the respective 230-kV transformer terminal. From this, a magnetizing impedance of 170 k Ω is calculated for the transformer (referred to the 230-kV terminals), or about 1000 pu on its rating. No significant oscillatory transients resulted from insertion of resistors into the circuit.

About 1.5 (60-Hz) cycles after resistor insertion, current was transferred to the main contacts on each phase. Figure 3 displays the resulting voltage transients on a typical closing operation. In this instance (Test #2C) main-contact current was initially established on B ϕ , producing a step voltage change on this phase. This was followed 0.5 ms later by W ϕ , and 4 ms later by R ϕ . Each main-contact closure is accompanied by transient oscillations at other transformer terminals due to electromagnetic coupling between windings. Three dominant frequency components result during the course of a three-phase, staggered pole closing operation. These are as follows.

At the instant of main-contact closure on the 230-kV winding, a 7-kHz transient results on the associated 500-kV winding terminal. Internal winding resonance is presumed to be the source of this oscillation. A peak transient overvoltage of 1.9 pu was recorded on one closing operation.

In addition, lower frequency transients at either 2 or 3 kHz result due to the distributed winding capacitance and the magnetic coupling between windings through the delta-connected tertiary. A 3-kHz oscillation results if the circuit is completed through main contacts on only one 230-kV phase, and 2-kHz if two phases. Calculations performed using the known transformer leakage reactance of 370 mH positive sequence and 430 mH zero sequence (500 kV base) show that these frequencies correspond to a capacitance to ground of about 5 nF connected at the 500-kV terminal.

3.2 Switching T7 Transformer using 500-kV Breakers

Two close-open switching operations were performed on PL504 and one on PL503. Once again, no significant transients resulted on breaker opening.

Transients on breaker closing were not unlike those caused by switching 230-kV breakers. One of the two 500-kV breakers (PL503) is equipped with 600 Ω per pole closing resistors, while the other (PL504) has none (Appendix B). However, transients produced on closing are similar in either case because of the comparatively large transformer magnetizing impedance (see Section 3.1). Maximum recorded transient overvoltages were less than 1.5 pu at transformer terminals. Figure 4 displays the resulting voltage transients on the 230-kV and 500-kV terminals respectively for one closing operation. Initiation of current in each breaker pole is accompanied by a step change in the line-to-ground potential on the corresponding 500-kV terminal. This

step change excites transient oscillations within the winding, which are then reflected at other transformer terminals.

A 7.5-kHz oscillation was recorded on the associated 230 kV-transformer terminal, presumably due to resonance in the switched phase winding. Recall that an internal resonance at 10 kHz was indicated by low voltage measurements done without transformer oil. This difference in frequencies is to be expected, and is consistent with the larger dielectric constant of transformer oil surrounding winding turns.

A 1-kHz transient results concurrently on the open 230-kV and 500-kV terminals with two breaker poles conducting. Once again winding capacitance and magnetic coupling between phase windings through the delta-connected tertiary is responsible, just as in the case of 2-kHz and 3-kHz oscillations for 230-kV switching. Calculations performed using this frequency value show that the equivalent capacitance to ground at the 230-kV terminal is about 90 nF. A slightly higher frequency (1.3 kHz) would be expected with one breaker pole conducting, but because first and second pole closures occurred within short times of each other during monitoring, this frequency cannot be validated from recorded results.

4. ASSESSMENT OF THE CAUSE OF TRANSFORMER FAILURE

The transformer and its tertiary reactor were being switched-out manually using the PL503 500-kV air-blast breaker when the transformer failed. It is now known that a flashover occurred from the vicinity of terminal 21 on the winding to the transformer neutral ground connection lead (Figure 2). Both 230-kV breakers were already open.

On the basis of our test results, there is no evidence that switching the transformer alone (i.e. without its tertiary reactor) using any of the transformer breakers could produce transient overvoltages high enough to account for the failure. Closing operations tend to be more severe than opening, producing transient voltages approaching 2 pu at the terminals. Transient voltages within the winding might well be higher (on a per-unit basis) because of internal winding oscillations. But winding insulation is presumably designed to withstand such transient overvoltages since these can occur routinely on all energizing operations.

On the other hand, transformers are known to have failed elsewhere under circumstances similar to those leading up to the failure at Hanmer TS. Investigations of these failures have indicated that switching of transformers along with their tertiary reactor using gas-blast breakers was a prime contributing factor/3/. It was concluded that high voltages could be generated internally on the winding due to part-winding resonance/4/ excited by multiple reignitions on the switched breaker.

4.1 Multiple Reignition Phenomena

Mechanisms associated with multiple reignitions on circuit breakers are discussed in depth in the literature/5,6/. A brief description of the relevant mechanism is given here for completeness.

When switching tertiary reactors along with the transformer using high-voltage breakers, the magnitude of inductive current being interrupted is small relative to the breakers' fault interruption capability. At Hanmer TS, the inductive load is 70 A rms referred to the 500-kV side, and 140 A rms on the 230-kV side. For multiple reignitions to occur in this duty, several conditions must be satisfied. First of all, contact-part on an opening operation must occur close to a 60-Hz current zero. This introduces a statistical element in the mechanism, so that not all opening operations are necessarily onerous. With contacts having parted close to a current zero,

the current may or may not be interrupted depending on the characteristics of the breaker. In general, interruption will not take place if the switching device is an oil circuit breaker. But if it is a gas-blast or a vacuum breaker, current may be interrupted initially even if contacts separate just past a current zero (due to current chopping; typically less than 10 A).

When breaker current is interrupted, energy is left stored on the load side in the form of trapped charge on terminal capacitance and possibly current in the inductive load (if current is chopped). An electrical oscillation therefore results between the inductive load and the terminal capacitance, whose frequency is relatively high (10's of kHz) because of the low terminal capacitance. The result is a large transient recovery voltage across a relatively small contact gap, which can conceivably cause a reignition across the opening breaker contacts. Should a reignition take place, a high-frequency current results through the breaker, whose initial magnitude is determined by the voltage existing across breaker poles at the instant of reignition. As this current oscillation decays, the breaker may interrupt again at one of the high-frequency current zeros. This is likely to occur if the switching device is a gas-blast breaker, and even more likely for a vacuum circuit breaker. Oil circuit breakers are inherently not capable of clearing at high frequency current zeros.

If current is interrupted, the entire sequence may then repeat itself, possibly occurring several times during the course of a single breaker opening operation. The possibility also exists during this sequence for relatively large transient overvoltages to be produced at the load terminals, but only if current interruptions occur at high-frequency current zeros.

From the foregoing description, several things are evident. Oil circuit breakers are inherently incapable of incurring multiple reignitions in this duty. On the other hand, air-blast or vacuum breakers may do so if contact-part on an opening operation occurs close to a 60-Hz current zero.

In breakers equipped with suitable opening resistors, however, the switching duty becomes largely resistive. Transient recovery voltage on the breaker is therefore reduced considerably, and the breaker is less likely to reignite. Even if a reignition were to occur, arcing is likely to continue until the next power-frequency current zero. By this time the contact-gap is much larger, hence the dielectric strength much greater, and therefore the current ought to be interrupted successfully. Breakers equipped with suitable opening resistors are therefore not likely to incur multiple reignitions on opening.

In the case of Hanmer TS, both the 500-kV air-blast breakers are likely to incur multiple reignitions when interrupting inductive loads. The transformer failure in fact did coincide with a switching operation on one of these breakers. Even though one of the 500-kV breakers (PL504) is equipped with 12 k Ω per pole opening resistors, the resistance is too large to effect a significant reduction in the recovery voltage impressed on the main contacts during opening. On the 230-kV side, both transformer breakers are identical oil circuit breakers, which are inherently not prone to multiple reignitions.

4.2 Implication of Breaker Reignitions

Occurrence of a single reignition on breaker opening is not considered a cause for concern. The resulting transients are not likely to be more severe than on breaker closing operations.

On the other hand, the possibility that repetitive current interruptions and reignitions during the course of an opening operation could excite electrical oscillations internally on transformer winding(s) cannot be ruled out. Each reignition would give rise to voltage transients similar in nature to those produced on closing (about 7.5 kHz in frequency). The magnitude of such

oscillations would vary, depending on the voltage existing across breaker poles prior to breakdown. At times, it might well be higher than that on closing. The superposition of all responses from each such reignition could produce significant overvoltages at 230-kV terminals as well as internally on the winding. While operation of arresters on the 230-kV terminals cannot be ruled out, this would not necessarily preclude the possibility of an internal winding-to-ground flashover. In fact, with conventional arresters, operation of the arrester itself could excite further oscillations internally on the winding due to the step voltage change produced by arrester sparkover. In this event, winding resonance would be excited in the 18-20 kHz frequency range, as indicated by low voltage measurements performed with a low impedance termination on transformer LV terminals (see Appendix A). As a consequence, even higher transient voltages could result internally on the winding.

Whether this was indeed the mechanism responsible for the failure may never be known for certain. There does, however, seem sufficient evidence in published literature to lend credence to this possibility/3/. The fact that windings on this transformer exhibit a resonance at low frequencies, which could account for high transient voltages at the point of failure, makes this mechanism a probable cause of failure.

5. SUMMARY & CONCLUSIONS

- (a) There is no evidence from the monitored full-scale switching operations or from low voltage surge transfer measurements at Hanmer TS, that switching of the transformer alone could create dielectric stresses high enough to account for the failure.
- (b) Results of low-voltage tests show that resonance in the winding can cause significant voltages to ground internally on the winding. Voltages to ground of eight to twelve times the applied sinusoidal excitation were measured at 8 kHz and in the 18-20 kHz frequency range.
- (c) It is expected that all gas-blast breakers (air-blast or SF₆) not equipped with suitable opening resistors could incur multiple reignitions when switching a transformer along with its associated tertiary reactor. This in turn could excite winding resonances. The 500-kV air-blast breakers PL503 and PL504 at Hanmer TS fall under this category.
- (d) Winding resonance internally on T7 is a probable cause for the failure experienced in September 1985. Switching of the tertiary reactor along with the transformer using 500-kV air-blast breaker PL503, which is not equipped with opening resistors, is considered a primary contributing factor.
- (e) Switching a transformer and its associated tertiary reactor using either oil circuit breakers or gas-blast breakers (air-blast or SF₆) equipped with suitable opening resistors is likely to be acceptable. Accordingly, switching of the tertiary reactor on T7 using 230-kV oil-circuit breakers HL23 and HL25 is likely to be acceptable.

6. RECOMMENDATIONS

- (a) Unless we have well-founded assurances from manufacturers that the respective transformer breakers are capable of switching reactors connected on transformer tertiaries without incurring multiple reignitions, this switching practice should be prohibited.
- (b) This restriction should be enforced rigidly in the case of all gas-blast breakers (air-blast and SF₆) not equipped with suitable opening resistors. On the other hand, for breakers

equipped with suitable opening resistors, and for all oil circuit breakers in general, it may be possible to waive the above restriction on the basis of results of controlled switching operations carried out to demonstrate satisfactory performance.

- (c) The switching restriction in place for 500-kV air-blast breakers at Hanmer TS should be continued.
- (d) It is expected that switching the tertiary reactor on T7 using 230-kV oil circuit breakers HL23 or HL25 would be acceptable. However before the existing operating restriction is revoked, suitable tests should be carried out to demonstrate satisfactory switching performance.
- (e) Analysis of the results of low voltage tests on the transformer (Appendix A) have raised issues concerning measurement techniques and interpretation of test results that should be addressed in any future tests:
 - (1) Effect of capacitive loading from instrumentation leads on transfer voltage measurements.
 - (2) Influence of eddy-current effects in core laminations on the measured winding response. This effect is likely to be more pronounced at frequencies up to about 10 kHz.
 - (3) Predictability of winding response, at resonance, to damped sinusoidal excitation, given the steady-state response for sustained excitation.

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APPENDIX A

RESULTS OF LOW-VOLTAGE MEASUREMENTS ON TRANSFORMER WINDING

Low voltage measurements were performed to look for part-winding resonances within the winding. A frequency range of 100 Hz to 100 kHz was selected for measurements. Excitation was applied to H3 in all cases due to time constraints. The magnitude of applied excitation was under 0.5 V rms for all frequency domain measurements and 10-30 V for time domain measurements.

A.1 Analysis of Results

Driving point impedance measurements (ie input impedance) performed with the 230-kV terminal left open show that series resonances exist in the winding at about 4 kHz and 10.5 kHz, while parallel resonances exist at about 4.5 kHz and 11 kHz (Figure A.1). If the 230-kV terminal is shorted to ground (ie transformer tank), then only a parallel resonance remains at about 4 kHz (Figure A.2).

Results of transfer voltage measurements lead to similar conclusions. Figures A.3 to A.5 show plots of voltage transfer functions for responses at the 230-kV terminal and two internal points on the winding (terminals 18 and 21 on transformer nameplate drawing - Figure 1). A dominant series resonance is indicated in the 8-9 kHz frequency range, which produces voltages-to-ground ranging in magnitudes from 8 to 12 times the applied sinusoidal excitation. Subsequent analysis suggests that this frequency would coincide with the 10.5 kHz resonance indicated by driving point impedance measurements, if it were not for capacitive loading due to measuring leads (30 m of 50- Ω co-axial cable). This is supported by results of measurements performed using short oscilloscope probe leads, which show a dominant 11 kHz oscillation on the 230-kV terminal when the associated 500-kV terminal is excited by an impulse (Figure A.7). Transfer voltage measurements also show that a series resonance exists at about 4 kHz, which is in agreement with driving point impedance measurement.

Tests were also performed with low impedance terminations on the 230-kV terminals to model the impedance of the 230-kV system. This might also model the situation where arresters on the 230-kV terminals have sparked over. With a 100- Ω resistor connected to each of the X terminals, the response on internal winding terminal 21 showed a series resonance at about 18.5 kHz (Figure A.6) as opposed to one at about 9 kHz with the X terminals left open (Figure A.5). Grounding the 230-kV terminals gave the same result as for 100- Ω terminations.

A.2 Winding Model at Resonance

Measured frequency responses can be used to synthesize models in the form of equivalent networks for use in computer studies. Such models are useful in studies requiring accurate terminal representation of the transformer. The approach involves fitting the response of a more or less arbitrary network to the measured data. The fitting procedure can be carried out rigorously to yield the desired degree of agreement with measurements over a specified frequency range/7,8/. In the present context, however, the simple series RLC circuit shown in Figure A.8 was used to model the 8-kHz series resonance on the 230-kV terminal. Starting from the known leakage impedance for the series winding (370 mH referred to the 500-kV side), a capacitance of 1.1 nF is computed to yield the desired resonance frequency. The resistor in the RLC circuit models losses in the resonant circuit. Its value is calculated as follows to limit the output voltage at resonance to 8 times the applied excitation, just as in measurements.

$$R = \omega L / G, \quad \text{where} \quad \begin{array}{l} \omega \text{ is the resonance frequency in radians/sec.} \\ L \text{ is the value of the inductor in H.} \\ \text{and} \quad G \text{ is the required voltage amplification at resonance.} \end{array}$$

This yields a resistance of 2.3 k Ω . Note though that this value of resistance is strictly applicable only at 8 kHz, since losses in the transformer are frequency dependent.

A.3 Effect of Measuring Leads on Experimental Results

This simple, though approximate model is helpful in analyzing the effect of capacitive loading due to measuring leads. Reducing the capacitance in the model by the estimated lead capacitance of 0.6 nF (referred to the 500-kV side) gives a resonance frequency of 11.7 kHz, which compares favourably with an 11-kHz transient recorded in surge transfer measurements. As a further check, measurements performed with a 0.01 μ F capacitor connected at the 230-kV terminal showed that the series resonance shifted to about 6 kHz. The model of Figure A.8 predicts 5 kHz.

A.4 Winding Response to Damped Sinusoidal Excitation

Voltage transfer measurements were also performed with damped sinusoidal excitation, since transients impinging on transformer terminals in normal service can be approximated by decaying oscillatory transients. Figure A.9 shows typical responses to such excitation. The shape of the response envelope is determined by two time constants, one characterizing losses in the resonant circuit and the other the rate of decay of the applied sinusoidal excitation. The combination of the two determines the peak magnitude attained by the response envelope/9/.

Time-domain tests were conducted for various rates of damping of the applied excitation. The plot of Figure A.10 shows how the measured response envelope peaks vary as a function of damping of the applied sinusoid for the three monitored locations on the winding. The variation is seen to be similar for all monitored locations. However, results of these time-domain measurements are at odds with earlier frequency-domain measurements. The response peaks corresponding to undamped excitation are lower for time-domain measurements. Taking as an example the response for terminal X3, the measured ratio of response voltage to applied voltage is about 5.6 from time-domain measurements (performed with 10-30 V excitation), and about 8 from frequency-domain measurements (about 0.2 V rms excitation Figure A.3). The reason for this discrepancy is not clear at this time. It may be a result of non-linear effects due to eddy currents in the iron core, or due to instrumentation limitations (eg current limiting on signal generator in time-domain measurements).

If we now compare the measured variation of response envelope peaks with that predicted by the model of Figure A.8, the results plotted in Figure A.11 are obtained. It is evident from this plot that except for the vertical offset between the two plots (which is due to the discrepancy noted in the previous paragraph), the model does reproduce the variation in response envelope peaks accurately.

APPENDIX B

CIRCUIT BREAKER SPECIFICATIONS

B.1 Circuit Breaker PL503:

Brown-Boveri Type DLF550q8 (Air Blast; Mfr date 1971)
Maximum Operating Voltage 550 kV
Continuous current 4 kA; Interruption 40 kA Symmetrical
1800 kV BIL; 1250 kV Switching Surge
Timing: Trip to contact part 23 ms
Close to contact touch 55ms
Maximum arcing time 12.5 ms
8 interrupters per pole:
600 Ω per pole closing resistors
No opening resistors

B.2 Circuit Breaker PL504:

Delle-Alsthom Type PK8B (Air-Blast, Mfr date 1965)
Maximum Operating Voltage: 525 kV
Continuous current 2.5 kA; Interruption: 33 kA Symmetrical
1900 kV BIL
2.5 cycle breaker
8 interrupters per pole:
No closing resistors
12 k Ω per pole opening resistors

B.3 Circuit Breakers HL23 & HL25:

General Electric Type FGK-230 (Oil circuit breaker)
Opening and Closing resistors:
252 k Ω per interrupter; 504 k Ω per pole

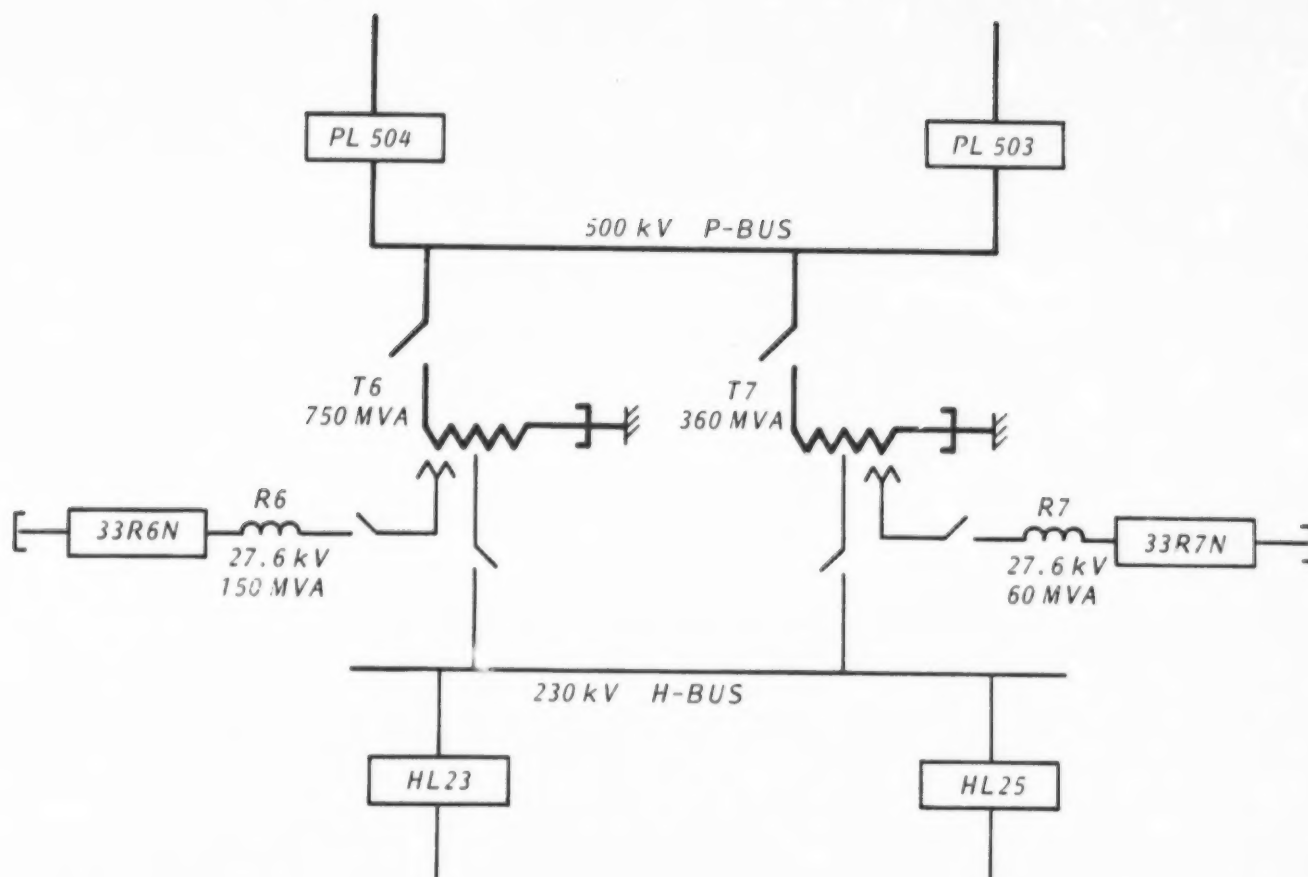
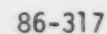


FIGURE 1
LAYOUT OF SWITCHGEAR ASSOCIATED WITH T7
AT HANMER TS



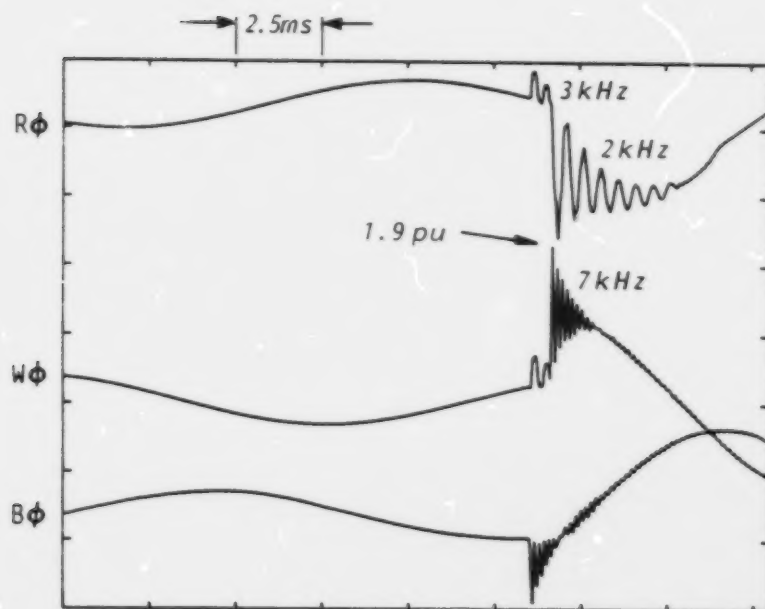
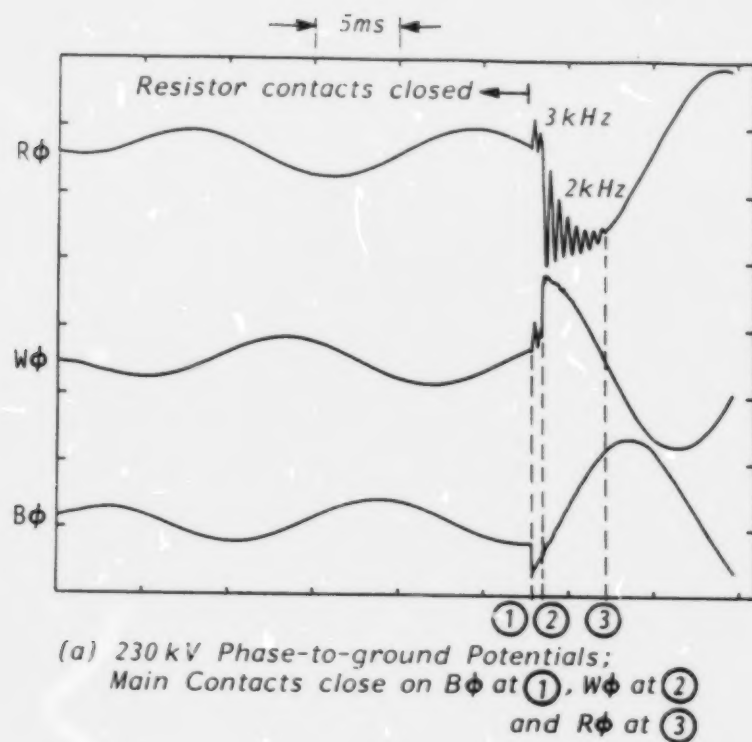
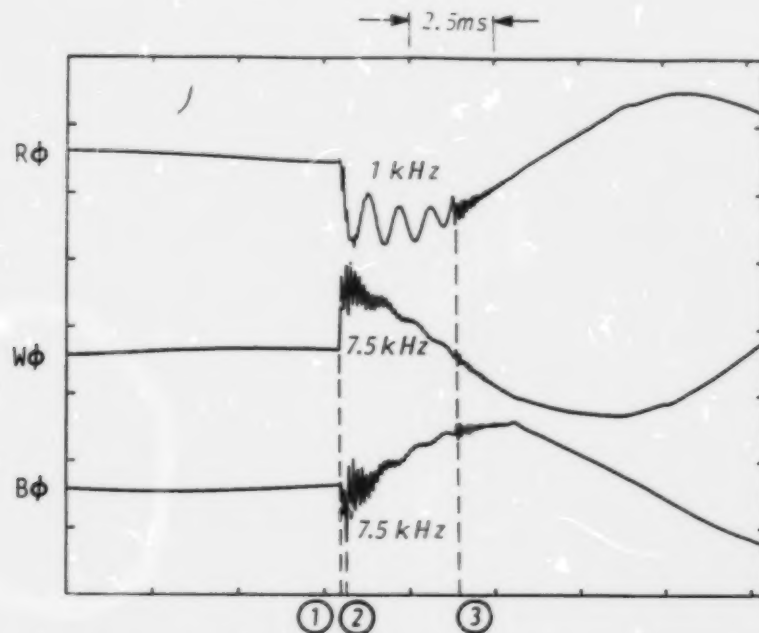
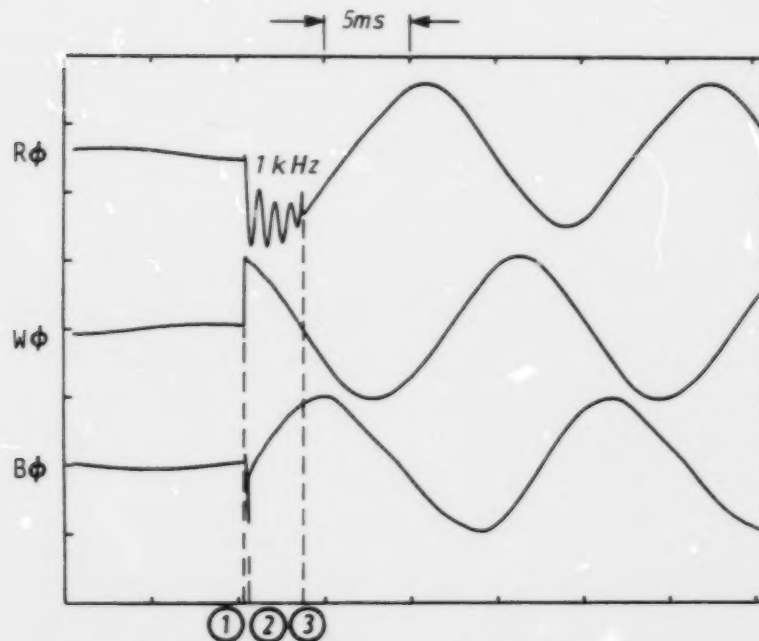


FIGURE 3
VOLTAGE TRANSIENTS RECORDED AT
TERMINALS OF T7 TRANSFORMER WHEN
CLOSING 230 kV BREAKER HL25 (TEST #2C)
AT HANMER TS



(a) 230 kV Phase-to-ground Potentials



(b) 500 kV Phase-to-ground Potentials;
Main Contacts Close on $W\phi$ at ①, $B\phi$ at ②
and $R\phi$ at ③

FIGURE 4
VOLTAGE TRANSIENTS RECORDED AT
TERMINALS OF T7 TRANSFORMER WHEN
CLOSING 500 kV BREAKER PL504 (TEST #4C)
AT HANMER TS

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITHOUT REACTOR R7
DRIVING POINT IMPEDANCE AT H3 WITH X3 OPEN

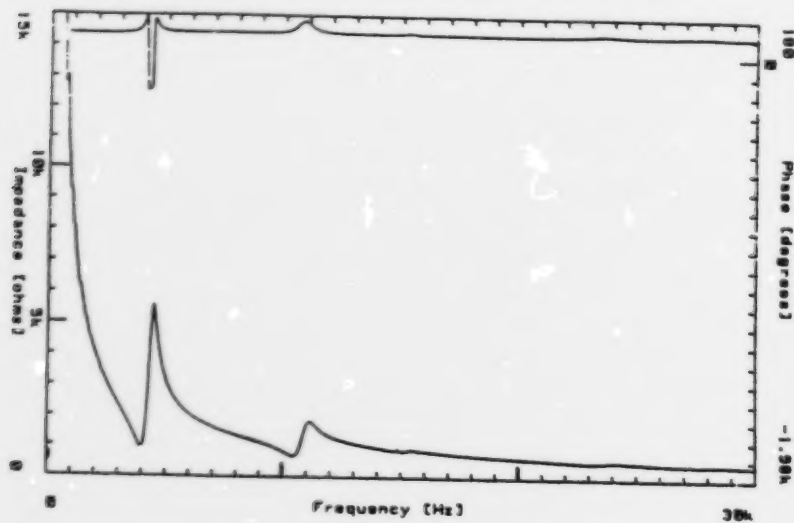


FIGURE A.1

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITHOUT REACTOR R7
DRIVING POINT IMPEDANCE AT H3 WITH X3 GROUNDED

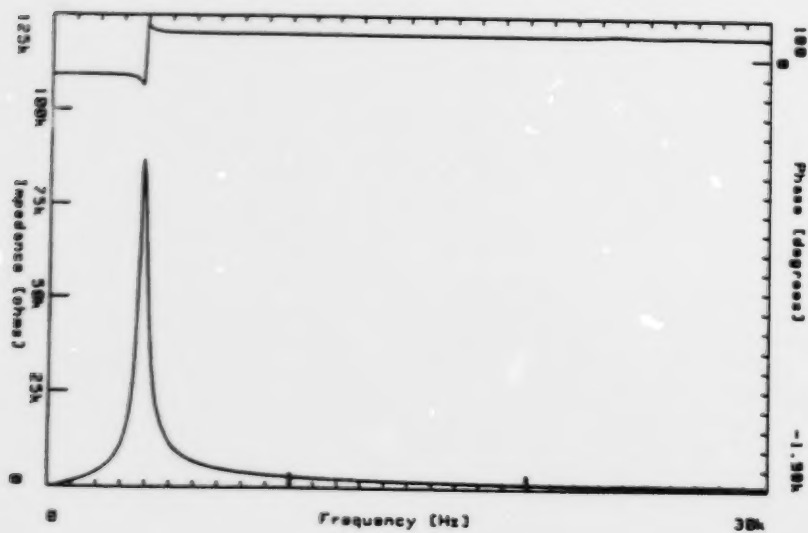


FIGURE A.2

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITHOUT REACTOR R7
EXCITATION ON H3 RESPONSE ON X3

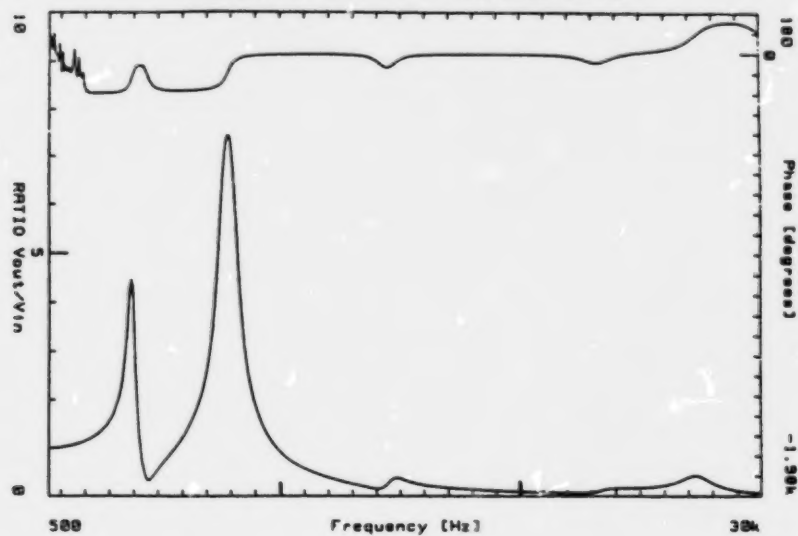


FIGURE A.3

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITH REACTOR R7
EXCITATION ON H3: RESPONSE ON INTERNAL WINDING TERMINALS 18&19

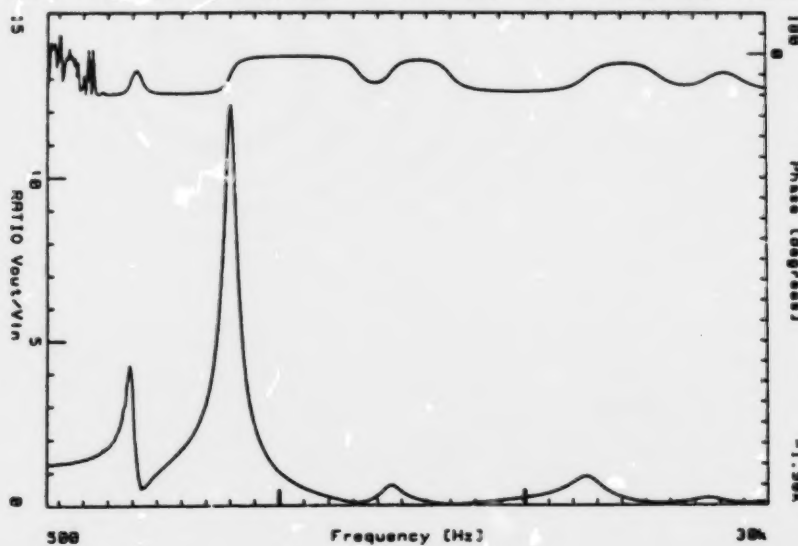


FIGURE A.4

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITHOUT REACTOR R7
EXCITATION ON H3 RESPONSE ON INTERNAL WINDING TERMINALS 21&23

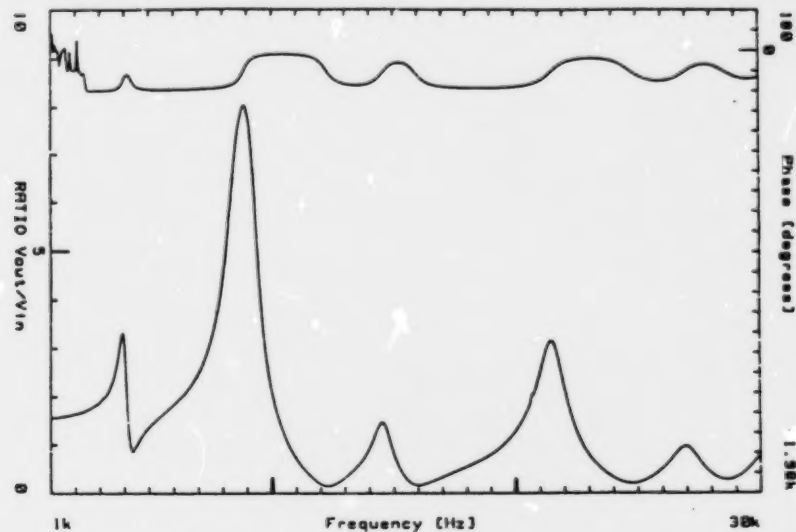


FIGURE A.5
MEASURED RESPONSE ON TERMINALS 21 & 23
WITH 230 kV TERMINALS OPEN

HANMER TS - FREQUENCY RESPONSE TESTS ON T7 B-PHASE, WITHOUT REACTOR R7
EXCITATION ON H3; RESPONSE ON TERMINALS #21&23; 100 Ohms TO GROUND ON X3

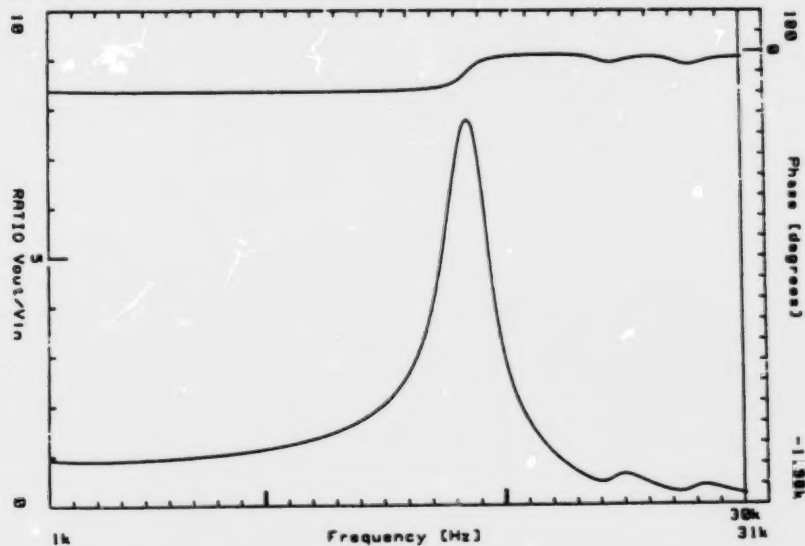


FIGURE A.6
MEASURED RESPONSE ON TERMINALS 21 & 23
WITH 100Ω ON 230 kV TERMINALS

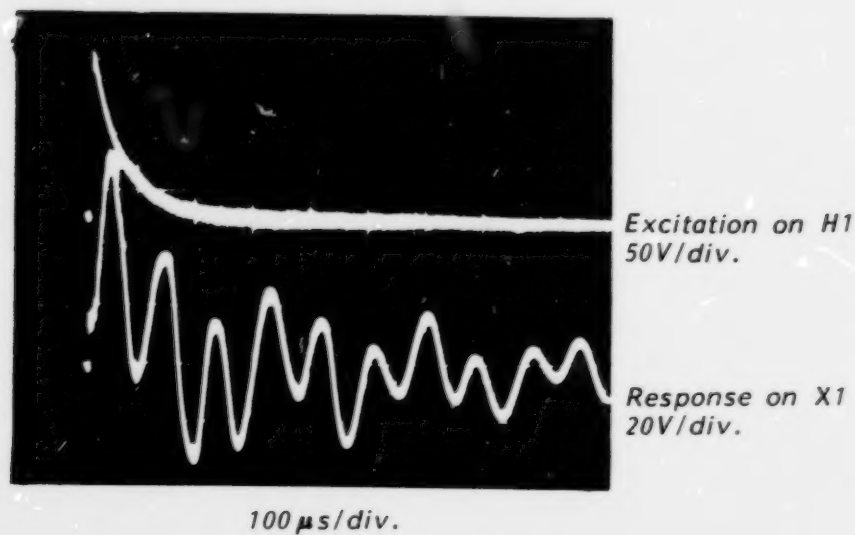


FIGURE A.7
MEASURED WINDING RESPONSE TO A $1.2 \times 50 \mu$ s IMPULSE

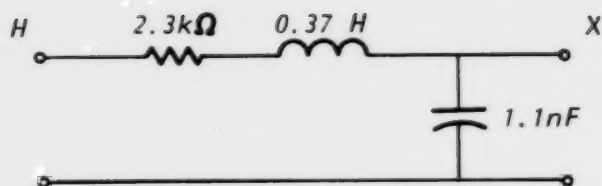
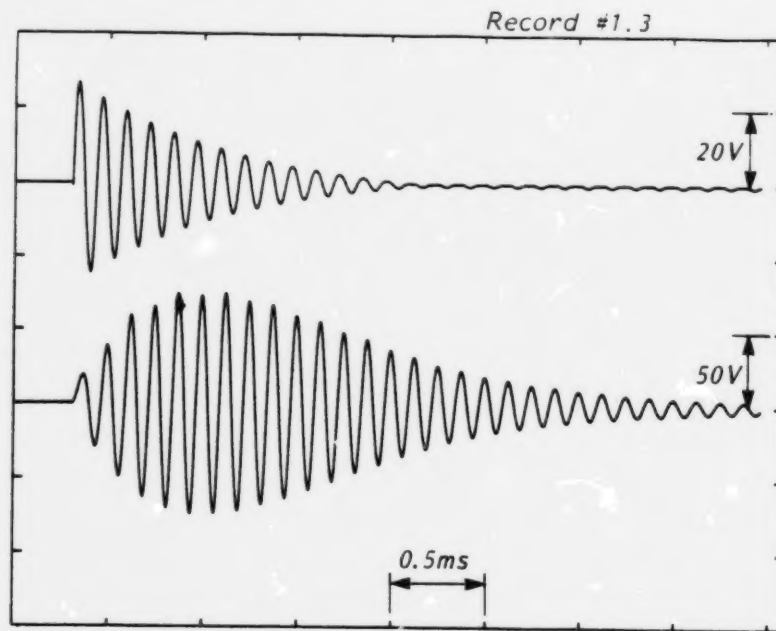
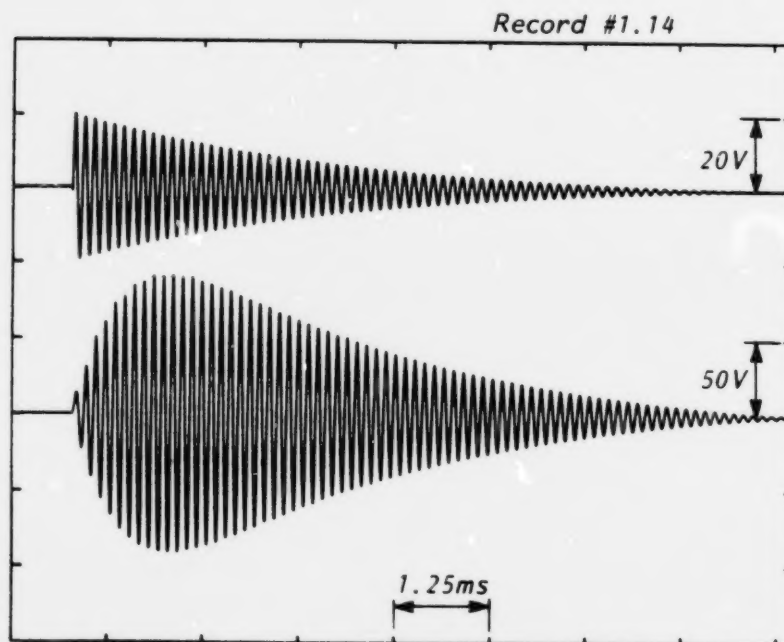


FIGURE A.8
NETWORK FOR MODELLING WINDING RESPONSE AT RESONANCE
(Resonance Frequency = 8 kHz)



(a) Excitation 8kHz, Damping Factor 0.84



(b) Excitation 8kHz, Damping Factor 0.96

FIGURE A.9
MEASURED RESPONSE AT INTERNAL WINDING TERMINAL 18
TO DAMPED SINUSOIDAL EXCITATION
AT RESONANCE FREQUENCY ON H3

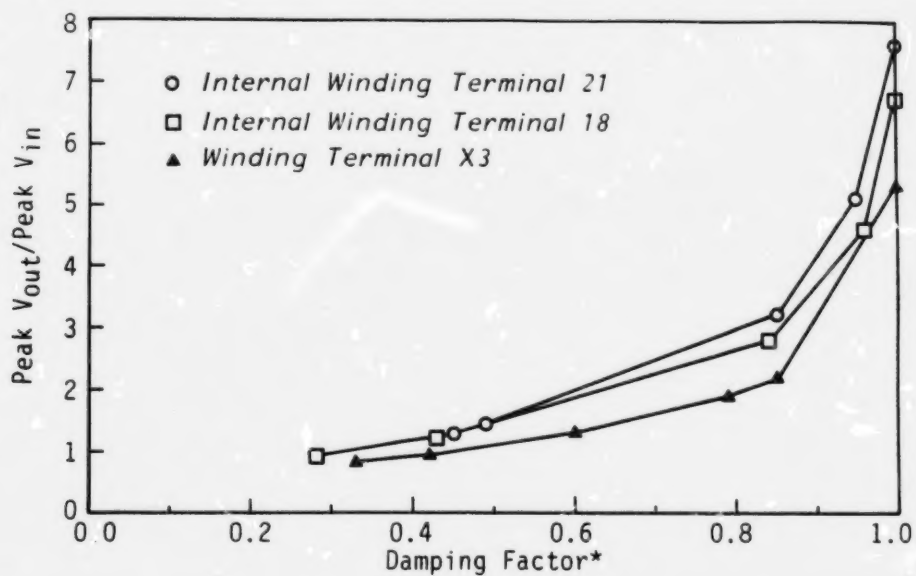


FIGURE A.10

MEASURED VARIATION OF RESPONSE ENVELOPE PEAKS FOR DAMPED SINUSOIDAL EXCITATION ON H3(10-30v PEAK)

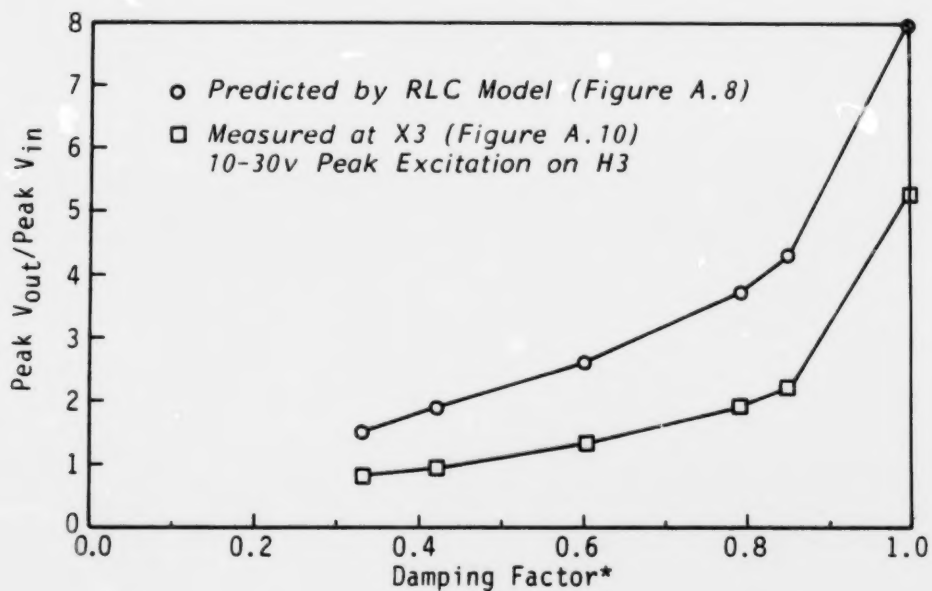


FIGURE A.11

VARIATION OF RESPONSE ENVELOPE PEAKS FOR DAMPED SINUSOIDAL EXCITATION

* Defined as a ratio of the magnitude of the first two peaks (same polarity) of the applied sinusoidal excitation. Equivalent time constant for rate of decay of applied sinusoid is $1/(8000 \ln D)$, where D is the Damping Factor.

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